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Icebreaking concepts that have potential application in the protection of offshore structures and drillships are reviewed. The concepts dealt with include conventional icebreaking by ships, icebreaking by air cushion vehicles, breaking against fixed structures, mechanical cutting with drag bit tools, blasting by high explosives, blasting with compressed gases or propellants, ice melting, thermal cutting, cutting with lasers, cutting with high pressure water jets, and unproven novel concepts. Special emphasis is given to the specific energy requirements for the various methods.

PREFACE

This report was prepared by Dr. Malcolm Mellor, Physical Scientist, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory, for the Department of Marine Geology, United States Geological Survey.

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ICEBREAKING CONCEPTS

Malcolm Mellor

Introduction

The purpose of these notes is to provide an outline of the various icebreaking concepts that are potentially applicable to the protection of offshore structures and drillships in ice-covered waters. The emphasis is on energy requirements for the different methods, and no attempt is made to assess the economics directly. The treatment is simplified in order to avoid the controversies and uncertainties of the detailed research literature.

Conventional icebreaking ships

The mechanics of icebreaking by ships is a controversial technical topic. There are numerous unresolved questions related to the basic mechanical properties of ice, to the flexure and fracture of ice plates under complex loads and deflections, and to the physical modeling of ship action in ice. The following notes represent an outsider's simplified approach to the overall dynamics and energetics of existing vessels operating in uniform sheets of unbroken ice. Since the concern here is with icebreaking, the resistance produced by mush ice, brash ice, and other well fragmented types of ice is not considered. The breaking of thick ice ridges is not dealt with because of scarcity of useable data.

In typical ship operations, floating ice sheets can be broken either by continuous travel through the ice, or by repetitive backing and charging. The latter mode involves inertial forces and dissipation of kinetic energy built up during the "charge", as actually employed, it is inherently inefficient in energetic terms, and the overall specific energy consumption can reach very high values. Consequently, any attempt to assess the energetics of this process would result in arbitrary numbers for a machine trying to operate beyond its real capabilities. This narrows the present consideration still further, to continuous-mode operation in uniform ice sheets.

During continuous-mode operation, the icebreaking process itself is discontinuous. Finite slabs of ice flex, break, and are displaced beneath and around the hull. Thus the forces needed to break the ice, to accelerate the fragments, and to move the fragments against hydrodynamic resistance all fluctuate at a moderately high frequency. However, the ship itself, having high inertia by virtue of its large mass, tends to proceed at approximately constant horizontal speed, without major high-frequency fluctuation of propeller thrust. Hence the icebreaking process can be characterized in terms of a constant horizontal force that represents the time-averaged value of the fluctuating resistance forces.

Icebreaking forces are estimated in a variety of ways. Estimates can be based on theory for elastic plates on elastic foundations, on extrapolations of model tests, from full scale ship tests, or from combinations of these things. All of the methods, with the possible exception of full scale tests, involve uncertainties, and there are disagreements between the resistance estimates of different investigators.

The USCG *Icebreaker Capability Reference Document* (Perrini, 1977) summarizes resistance calculations for a variety of existing and projected vessels, and compares the predictions based on the Kashteljan equations, on the Milano theory, and on model test results. In

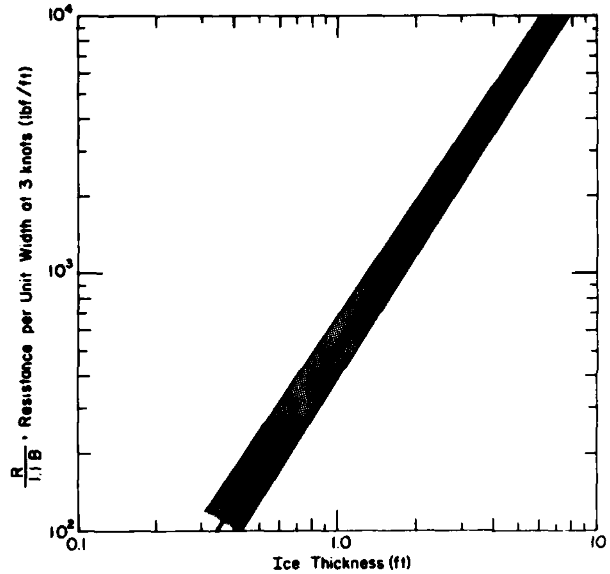


Figure 1. Mean predicted value of resistance per unit width as a function of ice thickness (existing icebreakers operating at 3 knots).

order to obtain representative values for ship resistance, "compromise curves" have been drawn between the Kashteljan, Milano, and model curves. For each class of ship represented in the document, mean values of resistance R as a function of ice thickness t have thus been obtained. The values of R for a ship speed of 3 knots are divided by the width of the broken swath to obtain a resistance per unit width. For this purpose, the width of the swath is taken as the ship's maximum beam at the waterline (B) plus 10%, i.e. $1.1B$ (it might be better to take B plus a multiple of the ice thickness, but $1.1B$ is an accepted rule of thumb in this field). The resulting composite plot for 12 classes of ships produced the data band shown in Figure 1.

The mean line drawn through the data band of Figure 1 can be described by the equation

$$R'/R'_1 = (t/t_1)^n \tag{1}$$

where R' is the resistance per unit width for ice thickness t, R'_1 and t_1 are reference values of unit resistance and thickness respectively, and n is a dimensionless exponent. For the line actually drawn, $n = 1.55$, or $n \approx 3/2$. Taking $t_1 = 1$ ft, $R'_1 = 520$ lbf/ft, so that eq (1) can be written as

$$R' = 520\,t^{1.55} \quad \text{lbf/ft} \tag{2}$$

when t is in feet. The uncertainty ranges from about ±30% in the thinnest ice to about ±20% in the thickest ice.

Because the detailed dynamics of the icebreaking process are complicated, it is useful to consider the energetics. The ship's available thrust T multiplied by the forward speed U gives the power which is applied to the ice; this is the effective horsepower, or ehp. The product of ice thickness t, width of broken swath W, and ship speed U gives the volume of ice broken per unit time, $\dot{V}$. The process specific energy E_s is thus

$$E_s = \text{ehp}/\dot{V} = T/tW. \tag{3}$$

But,

$$T/W = R' \tag{4}$$

and substituting from eq (2), the process specific energy at 3 knots can be expressed as

$$E_s = R'/t = 520t^{1.55}$$

$$= 520t^{0.55} \approx 520t^{1/2} \text{ lbf/ft}^2 \tag{5}$$

when t is in feet. To get E_s in units of lbf/in.^{2}

$$E_s = 3.61\,t^{0.55} \approx 3.61\,t^{1/2} \text{ lbf/in.}^2 \tag{6}$$

with t still measured in feet. Figure 2 shows this relationship, illustrating the increase in specific energy (i.e. decrease in efficiency) as ice thickness increases.

When ships are working at their maximum capability, the bigger vessels are breaking

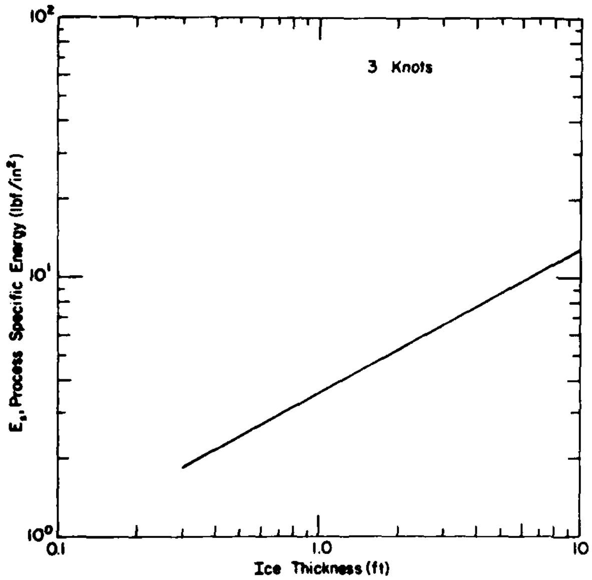


Figure 2. Process specific energy as a function of ice thickness for operation at 3 knots.

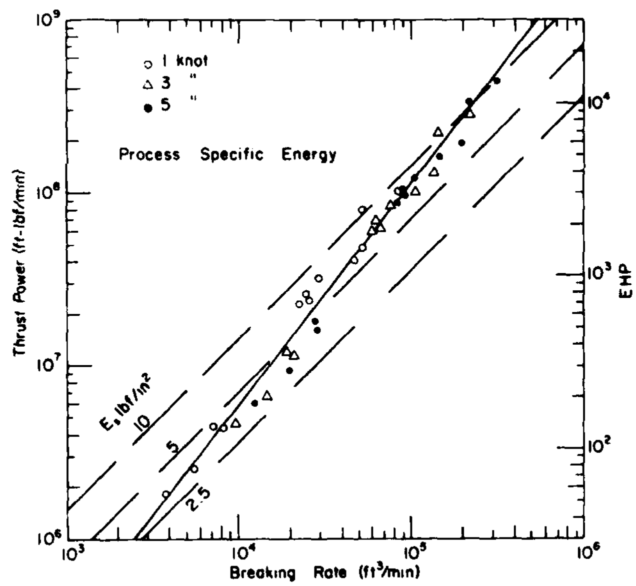


Figure 3. Thrust power of existing icebreakers (≈ eph) plotted against maximum volumetric icebreaking capability at 1, 3 and 5 knots. The broken lines indicate three constant values of process specific energy.

thicker ice, and consequently they can be expected to be less efficient than small ships (cf. Fig. 2). Representative values for the "ice thickness capability" of various classes of ships have been tabulated for 1, 3 and 5 knots, and the corresponding icebreaking rates have been calculated as the product of maximum workable ice thickness t, ship speed U, and swath width $1.1B$. Plotting these against the ship's available thrust power for corresponding speeds, a display of process specific energy for maximum capability is obtained (Fig. 3). It can be seen that E_s ranges from a low of about 3 lbf/in.^{2} for the small ships to a high around 10 lbf/in.^{2} for the big ships. Because the maximum workable ice thickness decreases somewhat for higher ship speeds, there is a tendency for E_s to decrease with ship speed.

The process specific energy does not take into account the inefficiencies of the ship as a thrusting device. The main inefficiencies are those of the propeller and the power plant. The main

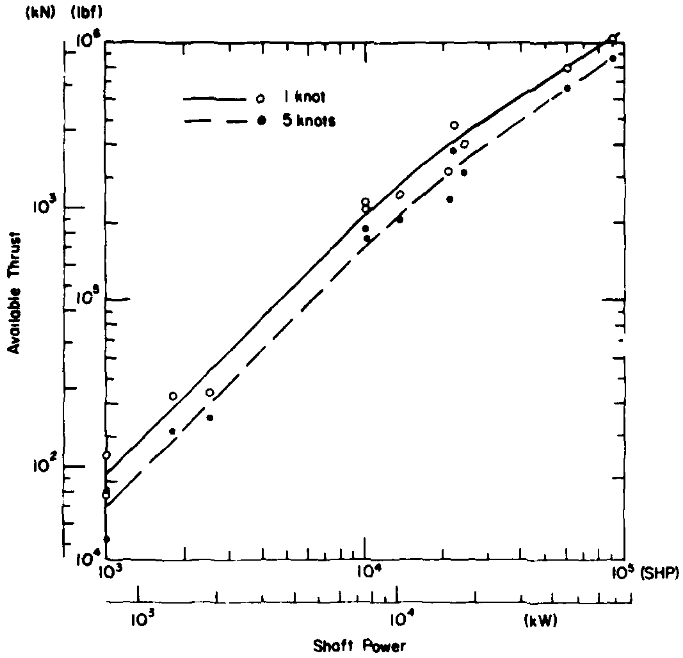


Figure 4. Available thrust as a function of shaft power for existing icebreakers operating at 1 and 5 knots.

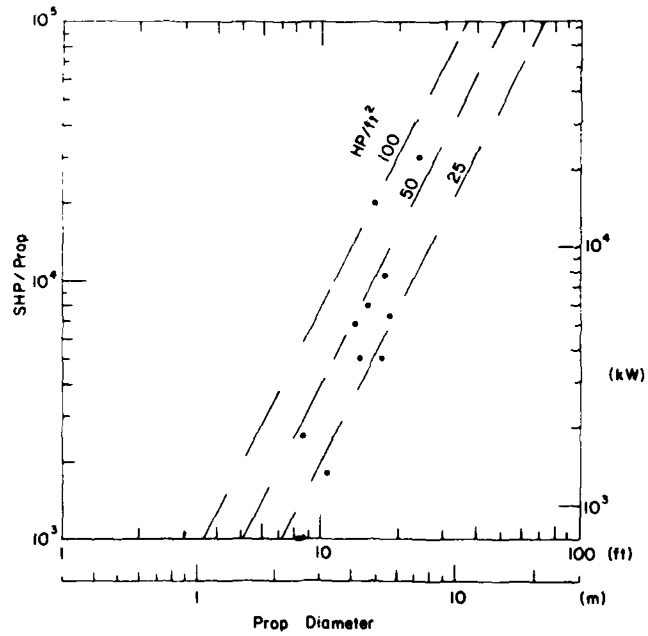


Figure 5. Shaft power available to each propeller plotted against propeller diameter for existing icebreakers.

source of concern is the propeller, which is likely to be very inefficient at the low speeds used for icebreaking.

A ship's propeller develops thrust by imparting momentum to the water. It develops maximum thrust when the ship's speed is zero, but in that condition its efficiency is zero, since the forward velocity is zero. As the ship's speed increases towards a limit set by the pitch of the propeller, the thrust decreases but the efficiency increases. The other big consideration is that the efficiency of a propeller decreases as the power density (power per unit area of propeller circle) increases.

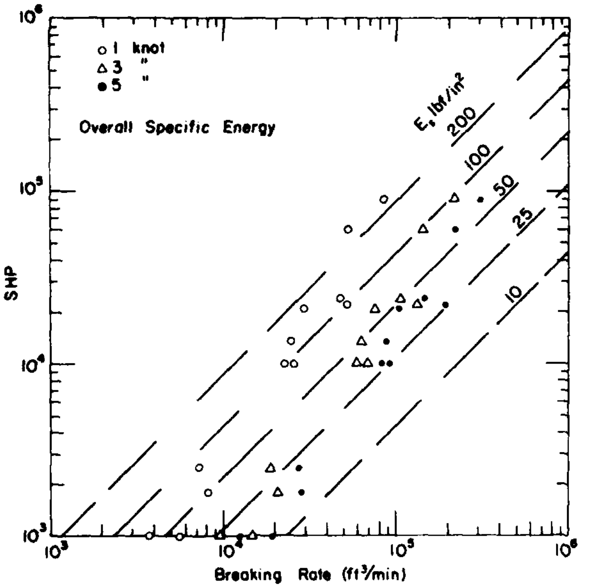


Figure 6. Plot of shaft power against maximum volumetric icebreaking rate for existing icebreakers operating at 1, 3 and 5 knots. The broken lines indicate values of constant overall specific energy.

Figure 4 uses data from the *Icebreaker Capability Reference Document* to show the relation between available thrust and shaft horsepower (shp) at 1 knot and 5 knots. The smaller ships (1000 to 10,000 shp) have almost as much low speed thrust (over 20 lbf/shp at 1 knot) as efficient tugs. However, as shp approaches 100,000 hp the unit thrust at 1 knot decreases to a value not much over 10 lbf/shp.

As a matter of interest in this connection, Figure 5 gives a plot of the shp per propeller against propeller diameter for existing (and projected) icebreakers. The general trend is for power to increase approximately with the cube of propeller diameter D, which means that the power density increases in proportion to $D^{1/2}$. This is what would be expected for geometrically similar hull forms and constant power/weight ratio.

Returning to the question of overall specific energy for icebreaking ships, Figure 6 gives a plot of shp against breaking rate for ships working at maximum ice thickness capability at 1, 3 and 5 knots. The proportionality lines show various levels of overall specific energy E_v. The range of E_v is from about 15 to 250 lbf/in.². Specific energy increases, and efficiency decreases, as the power increases. This is partly because the more powerful ships are breaking thicker ice, and partly because their propulsion is less efficient. Specific energy also increases as velocity decreases. This is because the limiting ice thickness increases as velocity decreases.

To sum up, the conventional icebreaker bow is a very efficient device for breaking ice. For typical vessels working at the limit of their capability, the process specific energy is at least an order of magnitude lower than the specific energy of an efficient mechanical cutter that uses high-speed drag bits. The process specific energy increases with ice thickness, approximately in proportion to the square root of thickness. Because conventional screw propulsion is inefficient at low speeds, the overall specific energy is much higher than the process specific energy. The overall specific energy of typical icebreakers is comparable to the specific energy of good mechanical cutters. The limiting performance of conventional icebreakers becomes progressively less efficient as size and power increase, since icebreaking resistance increases disproportionately with thickness, and propeller efficiency decreases as power density increases.

Icebreaking by air cushion vehicles

Air cushion vehicles have the ability to break ice. Two distinct modes of icebreaking can be distinguished: 1) low speed operation, in which the air cushion of the craft depresses the ice sheet and the exposed water surface adjacent to the free edge of the ice, 2) high speed operation, in which the moving craft sets up a wave that is of critical dimensions for flexure and fracture of the ice sheet. The high speed mode, which involves travel speeds of the order of 5 to 15 m/s, is

very much more effective than the low speed mode, causing the ice to break into large slabs over a swath that is considerably wider than the beam of the craft. However, the low speed mode, in which the broken swath is approximately equal to the beam, may be more compatible with the operation of a conventional ship if an icebreaking accessory is envisaged. For any given ice thickness the icebreaking effectiveness of an ACV ought to increase with the size of the craft, or more specifically with its lift area.

Even though airscrew propellers are very inefficient for propulsion at the relative low speeds of ACVs, the "high speed" icebreaking performance of ACVs seems to imply extremely small values of overall specific energy, i.e. extremely high icebreaking efficiency. From rough calculations, E_s appears to be of the order of 1 lbf/in.^{2}, which is at least an order of magnitude better than the overall specific energy of a conventional icebreaking ship.

A more detailed summary of the icebreaking potential of ACVs is being prepared at CRREL.

Icebreaking by fixed structures

A fixed structure resisting an encroaching sheet of ice may be regarded as an icebreaker. For a start, imagine an icebreaking ship anchored securely with its bow facing an advancing sheet of ice. In this case the ship itself consumes no energy, and the main concern is with the reaction force as the ice pushes and breaks against it. Figure 1 gives an impression of the force per unit width when the relative velocity is 3 knots. The unit force decreases as velocity decreases, but the lower limit of the data band in Figure 1 probably gives a fair estimate of the force levels for ice thrusting against an icebreaker bow.

A fixed offshore structure will usually be designed for omnidirectional operation relative to ice motion. For a rigid structure, a cone or an inverted cone provides suitable geometry for icebreaking by flexure, in much the same way as an icebreaker bow operates. If the conical structure is wide relative to the ice thickness, so that failure is by flexure, the horizontal breaking force ought to be comparable to the force on an icebreaker bow, though somewhat higher because of the smaller stress concentration factor. There are no direct measurements on large structures, but calculated values of horizontal breaking force based on the most credible and conservative theories are about 30% to 50% above the upper limit of the data band in Figure 1.

An isolated inverted cone in deep water is capable of displacing the broken ice underwater and allowing it to pass on with the flow. By contrast, a cone that forces ice upwards can accumulate ice fragments, and the friction involved in displacing these fragments can add significantly to the icebreaking forces. However, the advantages are not clearly with the inverted cone, since it is necessary to consider vertical force components and overturning moments on the structure.

Very wide vertical structures that crush or buckle the ice are inefficient for icebreaking, as are very narrow vertical structures that indent or crush the ice. Even cones can be inefficient if the diameter at ice level is not significantly greater than the ice thickness.

Mechanical cutting with drag bit tools

Mechanical ice cutters have been proposed or investigated for a variety of applications involving ships and offshore structures. As an aid to icebreaking by ships and river craft, it has been suggested that it would be useful to slice out cantilevers in the ice ahead of the bow. This cutting would be done by disc saws, chain saws, or vertical-axis milling cutters. It has also been suggested that the column of a monopod offshore structure could be protected by fitting it with a rotating ring of ice cutters, so that the column itself becomes a slot miller as ice encroaches.

For purposes of general analysis, machines and cutting tools have been classified according to the scheme shown in Figure 7. For present purposes, interest centers on transverse rotation machines, as represented by disc saws, wheel trenchers and milling drums, and also on continuous belt machines, as represented by large chain saws (coal saws and rock saws) and ladder trenchers. Possible cutting modes for these devices are illustrated in Figures 8 and 9.

The important operating parameters for a transverse rotation machine working in a given material are: 1) the rotational speed f, 2) the traverse speed U, 3) the rotor radius R, 4) the cutting depth d, 5) the cutting width B, 6) the rotor torque T, 7) the axle forces H and V, 8) the machine power P, 9) the power density of the active rotor surface Q, 10) the specific energy of the machine E_s. Figure 10 illustrates some of these symbols.

The important operating parameters for a continuous belt machine working in a given material are: 1) the belt speed u, 2) the traverse speed U,

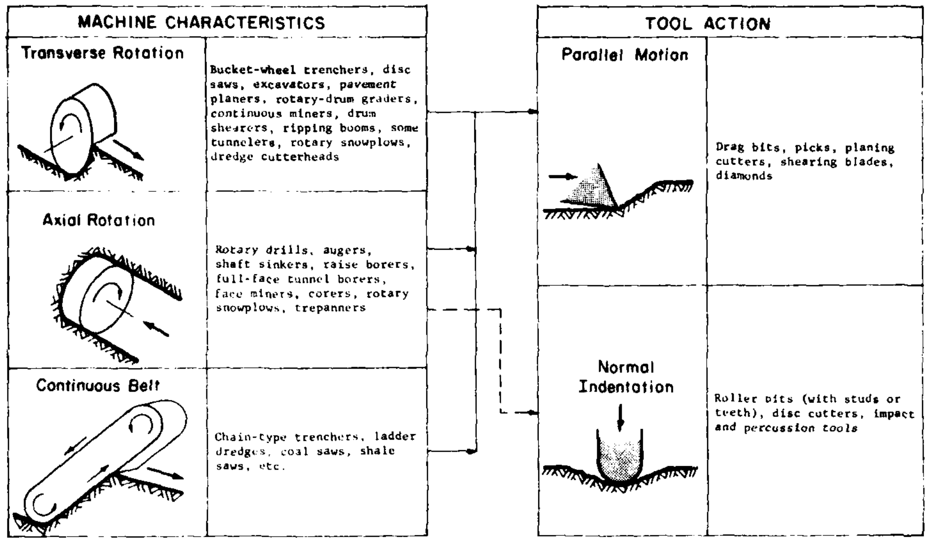


Figure 7. Classification of machines and cutting tools.

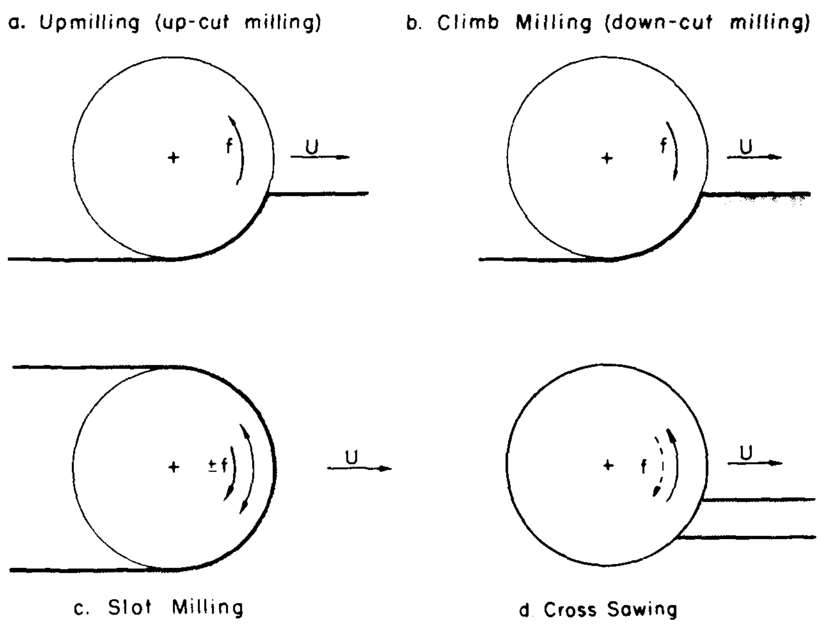


Figure 8. Cutting modes for transverse rotation devices.

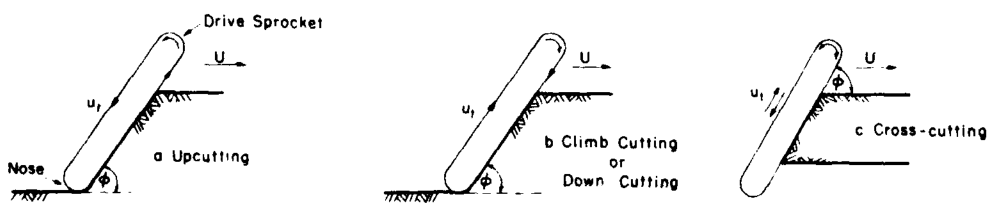


Figure 9. Cutting modes for continuous belt machines.

Table 1 Process specific energy for mechanical cutting of ice using drag bit tools.

Device or tool	Best values of process specific energy: lbf/in.² or in.-lbf/in.³	MN/m² or MJ/m³	Source for basic data
Machining on lathe and milling machine (1 mm depth of cut)	300-800	2.1-5.5	Mazur, T.M. (1974) Cutting of ice and its specific resistance. Internal Report LTR-LT-53, Division of Mechanical Engineering, National Research Council of Canada.
Machining on a lathe (5 mm depth of cut)	70-120	0.48-0.83	Bailey, J.J. (1967) A laboratory study of the specific energy of disengagement of frozen soils. Conducted by Creare, Inc., Hanover, N.H., for CRREL. CRREL Internal Report 99 (unpublished).
Test drilling with small augers	100-140	0.7-1.0	Kovacs, A., M. Mellor and P.V. Sellmann (1973) Drilling experiments in ice. CRREL Technical Note (unpublished).
Test drilling with small augers	300	2.1	Sellmann, P.V. and M. Mellor (1974) Man-portable drill for ice and frozen ground—Preliminary development report. CRREL Technical Note (unpublished).
Tests of small auger	57	0.39	Kovacs, A. (1974) Ice augers (continuous flight, lightweight, man-portable). CRREL Technical Note (unpublished).
Tests of large experimental ice saw (modified coal saw)	406-518	2.8-3.6	Garfield, D.E., B. Hanamoto and M. Mellor (1976) Development of large ice saws. CRREL Report 76-47.
Tests of large chain saw (lumber saw)	1220-3056	8.4-21	Garfield et al., 1976
Experimental rotary ice miller	1140*	7.9	Frankenstein, G. (1965) USACRREL ice chipper. CRREL Special Report 73.
Large rotary-drum ice miller	70-140	0.48-1.0	Gifford, S.E. (1966) Ice-grading equipment—Icedozer for pioneering in rough ice. Technical Report R-468, U.S. Naval Civil Engineering Laboratory.
Commercial coal saw	1740*	12	Dean, R.C. (1962) Drilling and excavating in ice and frozen soil. CRREL Internal Report 148.
Commercial continuous miner	280	1.9	Abel, J.F. (1961) Under-ice mining techniques. U.S. Army Snow, Ice and Permafrost Research Establishment (SIPRE) Technical Report 72. AD652711.
Laboratory drag bit tests	200	1.4	Peng, T. (1958) The investigation of ice cutting process. SIPRE Internal Report 87 (unpublished)
Laboratory tests with 63.5 mm dia. milling cutters	170	1.2	Bonz, P.E. (1973) 24-foot experimental river icebreaker development program. Report by Consultec Inc. for U.S. Coast Guard Office of Research & Development, Report No. 731343.
Tests of 102 mm dia. milling cutters on floating ice	160-190	1.1-1.3	Bonz, 1973
Tests of chain saw on floating ice	1430 (4670 typical)	9.9	Bonz, 1973
Tests of soil trencher fitted with special teeth	172-219	1.2-1.5	Vaudrey, K.D. (1977) An ice excavation machine. Technical Report R851, Civil Engineering Laboratory, U.S. Navy.
Tests of special ice-cutting drum mounted on backhoe boom	730-860	5.0-5.9	Vaudrey, 1977
Tests of 457 mm dia. circular saws cutting floating ice	340 (field) 290-320 (lab)	2.3 2.0-2.2	Lecourt, E.J., J.W. Lewis, T. Kotras and J.C. Roth (1973) Mechanical ice cutter. Design and testing of ⅛th scale model. Report by Arctec Inc. (TR0071-2) for U.S. Coast Guard, Office of Research and Development.

*No allowance made for power losses in the transmission and drive train.

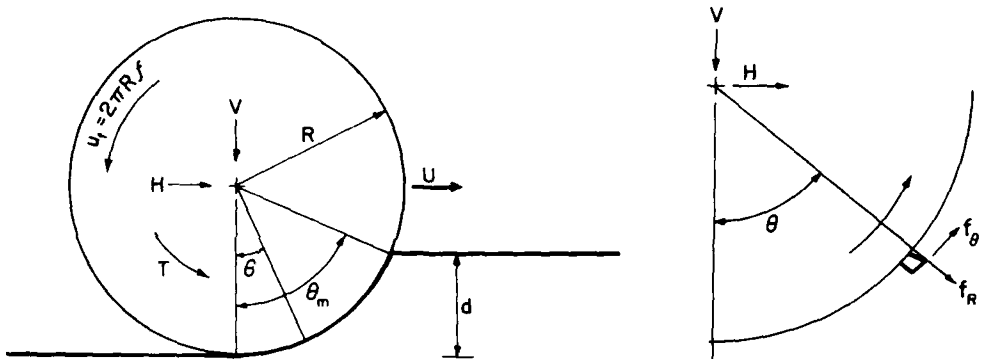


Figure 10. Definition of analytical symbols for rotary machines.

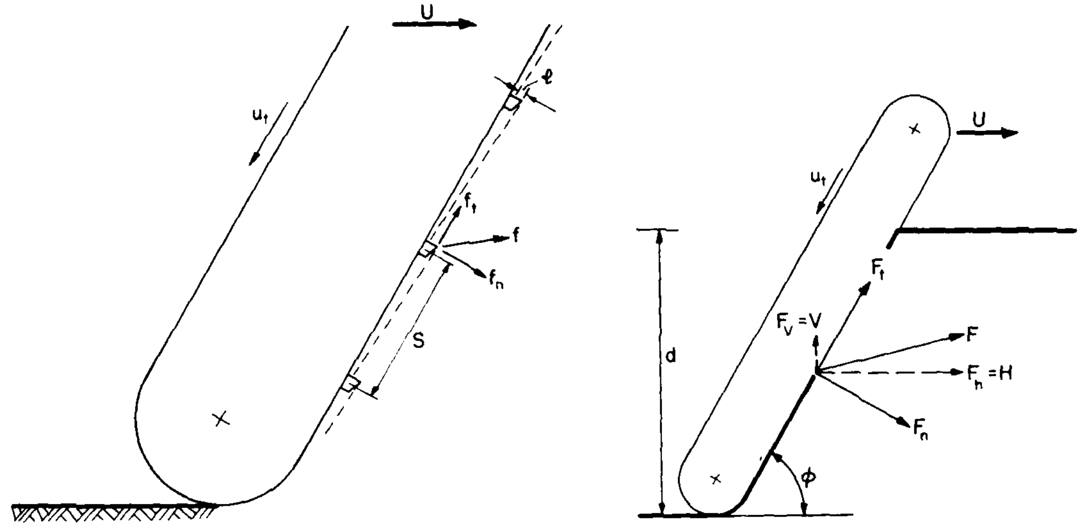


Figure 11. Definition of analytical symbols for belt machines.

3) the bar angle ϕ, 4) the cutting depth d, 5) the cutting width B, 6) the chain force F_c, 7) the reaction forces, H and V or F_h and F_v, 8) the machine power P, 9) the power density of the working area Q, 10) the specific energy of the machine E_s. Figure 11 defines some of these symbols.

For the cutting tools on machines of either type, the important parameters for work in a given material are: 1) the rake angle β_1, 2) the relief angle β_2, 3) the included angle β_3, 4) the side rake, side relief, and base angles, β_4, β_5, β_6, 5) the tip radius r, 6) the chipping depth ℓ, 7) the effective tool width w, 8) the cutting force f and its orthogonal components f_t and f_n, 9) the cutting speed u, 10) the specific energy of the tool E_s. Figures 12, 13 and 14 illustrate the meanings of some of these symbols.

For most applications involving the cutting of floating ice, there is an additional factor arising from the hydrodynamic resistance on partially immersed cutters, and the added water mass to be considered along with clearance of cuttings.

The relevant theory for machine design is too complicated to be summarized here. However, it is important to know that it exists. Some past developments of ice-cutting machinery have been pervaded by confusion, leading to poor performance of prototypes and erroneous conclusions about proposed concepts. In addition to theory, it is necessary to understand the practical limitations of structures and mechanisms.

To provide a general impression of probable machine characteristics, a few numerical values can be given.

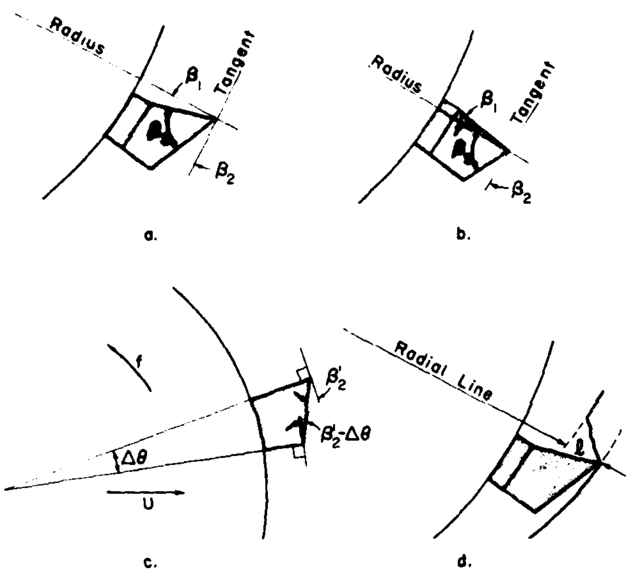


Figure 12. Geometry of typical cutting tools on rotary machines.

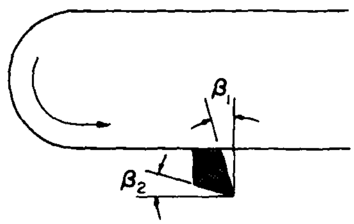


Figure 13. Definition of apparent rake angle β_1 and apparent relief angle β_2 on belt machines.

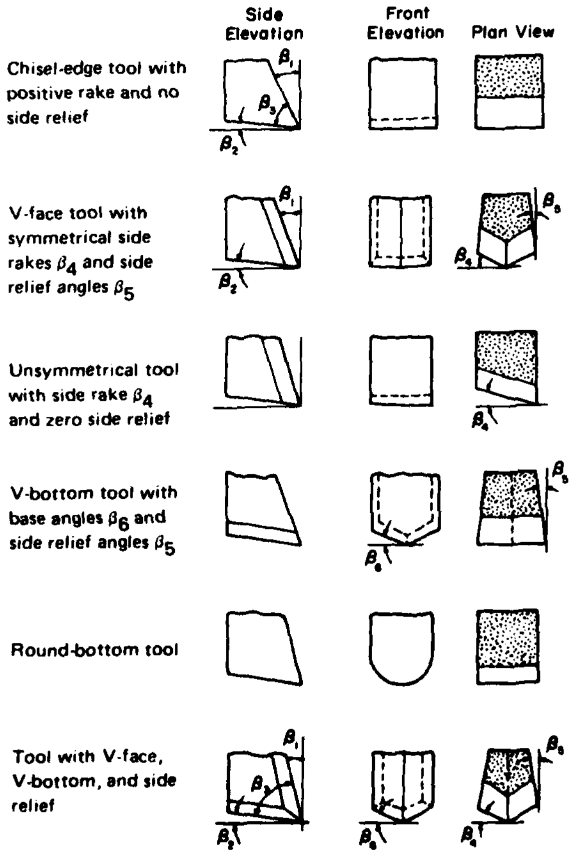


Figure 14. Designation of tool angles for drag bits.

The tangential speed of tools on a rotor or a belt is likely to be in the range 100 to 1000 ft/min (0.5 to 5 m/s). At the low end of this range, forces and torques tend to become unmanageably high. At the top end of the range there may be efficiency problems due to very small chipping depth, and the inertial effects of chip discharge become significant. On belt machines there may be mechanical problems with high-speed chains.

Because tool spacing can only vary within certain limits, the necessity for control of chipping depth means that there has to be a relation between traverse speed U and tool speed u. For efficient working, it is likely that U/u will be of the order of 10^{-2}, i.e. greater than 10^{-3} but appreciably less than 10^{-1}.

A practical upper limit to the cutting capabilities of a machine are set by the lowest attainable value of the specific energy E_s for drag bit cutting in ice. A convenient definition for the process specific energy E_s is the cutting power divided by the volumetric cutting rate. In this, the power is that actually delivered by the cutters, without taking into account power losses within the machine's drive system. A realistic minimum value of E_s for a big machine cutting ice is 100 lbf/in.^{2} (≡ in.-lbf/in.^{3}), or 0.7 MN/m^2 (≡ MJ/m^3). However, it should be remembered that with inappropriate design or improper operation, E_s could be 10 times this value. Knowing E_s, the volumetric cutting rate for a given power level can be estimated or, alternatively, the required power for a specified cutting rate can be estimated. If the overall specific energy of the machine is required, it is obtained by dividing the total input power by the volumetric cutting rate. In many cases the difference is largely attributable to losses in the drive system, so that overall specific energy is approximately the process specific energy divided by the transmission efficiency.

It might seem that any level of cutting performance could be achieved with a particular device, given enough power. This is not the case, since there is a practical limit to the useful power density of a cutting surface. At the present time, the limit might be about 40 hp/ft^2, or 0.3 MW/m^2, for big rotary and belt machines.

With the power density and the tangential tool speed fixed, the average pressure on the cutting area is more or less determined because of the fixed ratio of normal to tangential tool force components for any given tool design and state of tool wear. This average pressure might be about 10 to 30 lbf/in.^{2} (70 to 200 kN/m^2) with typical unworn cutting tools.

The general thrust forces on the cutting devices are controlled by the power being utilized, the dimensions of the rotor or bar, the depth of cut relative to radius for a rotor, the bar angle for a belt machine, the design details of the cutting tools, and the state of wear of the cutters. These things cannot be summarized very concisely. However, it might be worth correcting the widespread misconception that the resultant cutting force of a slot miller is aligned with the direction of straight-line travel (something that is obvious to anyone who has used a power hand router for woodworking).

A good deal of publicity has been given to oil industry proposals for a rotating collar ice cutter to protect and maneuver a monopod structure or semi-submersible drilling vessel. The published design projections (see, for example, *Oilweek*, 18 November 1974, and *Offshore Engineer Supplement*, December 1977) for this device are not credible, as has been illustrated by specimen calculations in a relevant design text (Mellor, 1977).

Icebreaking by high explosives

Both sheet ice and massive ice can be broken by high explosives. However, it should not be imagined that ice is so fragile that superb results will be obtained with explosives; weak materials of low density may be easy to break and displace, but they tend to be very effective in attenuating stress waves.

To break floating sheet ice, the most efficient procedure is to place explosive charges in the water just beneath the ice. Most of the energy of the explosive goes into creating a gas bubble, and ideally this rapidly expanding bubble would be used to dome the ice and break it purely in flexure. However, if the charge is close enough to the ice for its bubble to be used effectively, the shock wave, or stress wave, which precedes the bubble will shatter a small hole above the charge, and thus allow some venting of the gas.

The main objective in icebreaking is to break the maximum amount of ice for a given amount of explosive. The next most important goal is to place the explosive charge as efficiently as possible.

To obtain maximum breakage it is necessary to consider: 1) the ice thickness, 2) the desired width of the break, 3) the depth of the charge. The necessary design data have been obtained

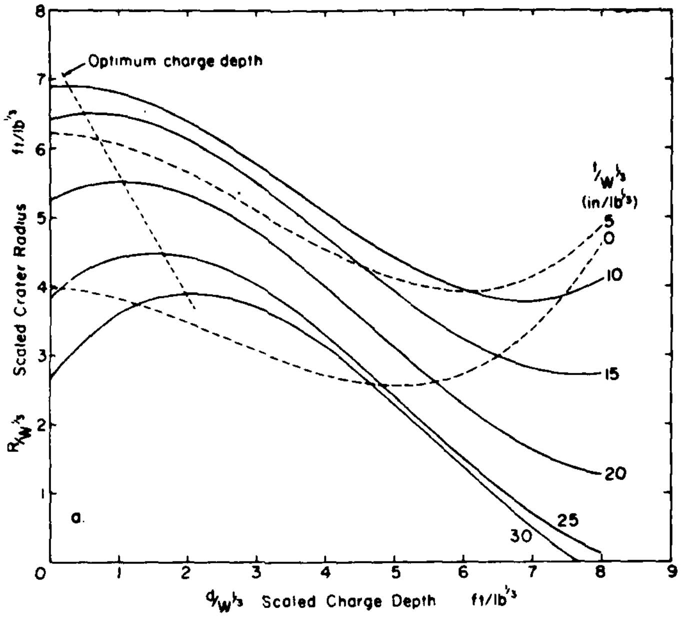


Figure 15a. Scaled crater radius as a function of scaled charge depth for a range of scaled ice thicknesses.

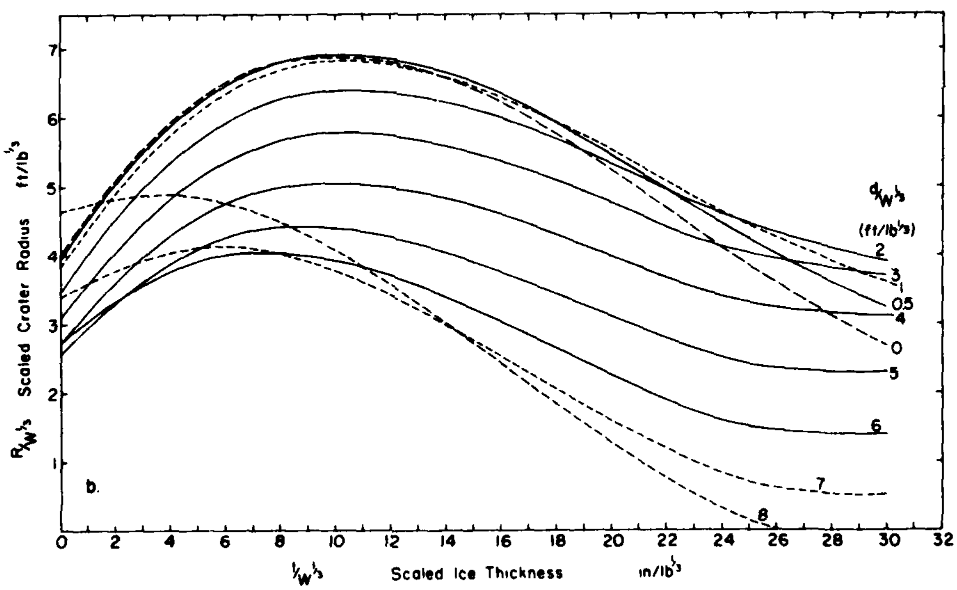


Figure 15b. Scaled crater radius as a function of scaled ice thickness, with scaled charge depth as parameter.

by multiple regression analysis of all available test data for single charges, leading to the curves given in Figure 15 (Mellor, 1972). The use of these curves is best explained by a numerical example.

Suppose that a 25-m swath is to be broken by a single line of concentrated charges through ice that is 2 m thick. We can take 12.5 m as the required crater radius, assuming that the ship can break out the cusps between overlapping holes. There is an optimum charge weight for ice that is 2 m thick, and an optimum charge weight for a

crater radius of 12.5 m, but the two are not necessarily the same. The object is to find the best compromise.

The best possible result occurs when $R/W^{1/3} \approx$ 6.9 ft/lb$^{1/3}$, and if R = 12.5 m this implies a charge weight of 210 lb. With this charge weight, the scaled ice thickness for t = 2 m is 13.25 in./lb$^{1/3}$. This is greater than the value of $t/w^{1/3}$ = 10 in./lb$^{1/3}$ which gives best results in terms of ice thickness, but because the curves in Figure 15(b) have broad peaks it does not make very much difference. If we step up the charge weight to 250 lb and place it at optimum depth, the scaled ice thickness becomes 12.5 in./lb$^{1/3}$ and the scaled crater radius about 6.8 ft/lb$^{1/3}$. This means that the actual crater diameter will be 26 m. There are many uncertainties and variations with blast effects, so that this estimate is close enough for practical purposes. The spacing between charges is a matter for judgment, but presumably it would be approximately equal to the crater diameter (too much overlap is undesirable because the effectiveness of a charge is reduced by adjacent open water).

This covers charge design and provides an idea of the magnitude of required charge sizes, but it still leaves the question of how to place charges under the ice.

A standard method for placing charges is drilling, using special equipment developed for ice. This method can be used for protecting structures against encroaching ice, but it may not be very suitable for breaking out ship channels. There are other possibilities, such as towing a string of charges under the ice, or using divers to set charges, but these have not been developed for operational use.

To sum up the technical data for blasting of uniform floating ice sheets, the best results are obtained when 1) the charge is almost in contact with the underside of the ice, 2) the crater radius is about 8 times the ice thickness, 3) the yield is about 125 ft^3/lb (7.8 m^3/kg). Knowing the yield of a blast in terms of volume broken per unit weight of explosive, we can calculate the specific energy in terms of energy per unit volume if the energy density of the explosive is known. For typical explosives and blasting agents the heat of explosion is highly variable, but for present purposes we take 1 kcal/g as a representative value. With optimum yield of 7.8 m^3/kg and a heat of explosion of 1 kcal/g, the specific energy is 0.54 MJ/m^3, or 78 lbf/in.^{2}.

For blasting massive ice the procedures are different. Relevant technical data have been given by Mellor et al. (1977).

Blasting with compressed gases or propellants

In conventional blasting of floating ice with high explosives, the initial shock wave is of no great value, and it may well detract from the effectiveness of the expanding gas bubble. It is therefore worth considering the use of compressed gas devices, deflagration processes, and low explosive propellants.

Two commercial gas-blasting systems have been tested for icebreaking (Mellor and Kovacs, 1972). These are the Airdox system, in which air is compressed to 12,000 lbf/in.^{2} and then discharged abruptly, and the Cardox system, in which liquid carbon dioxide is abruptly vaporized by an electric heating element and discharged at high pressure. The volume of gas released in a single discharge is limited for both systems, and therefore there is a limit to the thickness of ice that can be broken (about 2 ft). However, when operated to best advantage the process specific energy for these devices was approximately 35 lbf/in.^{2}, or 0.23 MJ/m^3 (based on the energy of the expanding gases only).

Another approach to gas blasting is based on special devices that ignite fuel/air mixtures. One such device was designed specifically for breaking floating ice. It had a 5-ft^3 combustion chamber that was charged with a mixture of propane and compressed air to pressures in the range 60 to 95 lbf/in.^{2}. The venting port of the combustion chamber was slid beneath the ice, the mixture was ignited by a spark plug, and as the chamber pressure increased by a factor of 6 the gas was discharged. For an initial charge pressure of 80 lbf/in.^{2} the potential energy of the blast was approximately 1.25×10^6 ft-lbf, which is about the same as the energy of standard Airdox and Cardox shells. However, the fuel/air combustion device was less effective than the high pressure systems, reaching the limit of its capability with 1 ft of ice.

The fuel/oxidant combustion system has a number of attractive features for repetitive blasting, and with more careful design it could be made to break thick ice. Design calculations should take into account the combustion process, the behavior of gas bubbles in water, the bearing strength of ice plates, and the inertial response of ice plates.

Self-oxidizing low explosives have not been used much for icebreaking since the days of gun-

powder. From test data given by Van der Kley (1965) the best yield for icebreaking with gunpowder was 0.23 kg/m^3. Taking the heat of explosion for black powder as 665 cal/g, the corresponding specific energy is 0.64 MJ/m^3, which is about the same as a good value for high explosives doing the same job. However, low explosives, which deflagrate rather than detonate, can be used in gun barrels and against steel structures.

Melting ice

In principle, it is possible to clear a channel through ice by melting it. This is not likely to be a practical method for anything other than very slow encroachment of ice against a fixed structure, but it is useful to establish the energetics of melting as a datum for assessment of other processes.

To melt freshwater ice from a temperature of -5°C, the specific energy consumption is 4.58×10^4 lbf/in.^{2}, or 316 MJ/m^3 (MN/m^2). For sea ice, the heat of melting varies with the starting temperature, the salinity and the density, but as a representative value of specific energy for 100% thermal efficiency we can take 4.21×10^4 lbf/in.^{2}, or 290 MJ/m^3.

Just to give an idea of how outrageous a straight melting process would be, we might note that to completely melt a channel through sea ice 2 m thick for an icebreaker that has an effective beam of 25 m and a speed of 3 knots, the required power at 100% efficiency would be 22,400 MW, or 30 million horsepower.

Thermal cutters

While bulk melting is clearly impractical, there is a possibility of using thermal devices to cut thin slits in the ice. The process specific energy for melting is very high, but in principle the required input power can be kept within bounds if melting is confined to a narrow slit.

The main concern with a thermal cutter is to achieve a sufficiently high penetration rate. The rate of melting at a surface is limited by the attainable power density and the heat transfer process. If u is the penetration rate of a thermal cutter, Q its power density, and E_s the specific energy for melting, then

$$u = Q/E_s.$$

Taking E_s = 290 MJ/m^3 for typical sea ice, and Q = 3 MW/m^2 as a maximum attainable power density for submersible electrothermal devices, the maximum penetration rate at 100% thermal efficiency is about 0.01 m/s, or 2 ft/min. Thus if the rate of cutting in the horizontal direction has to be much higher than this rate (1 knot is 50 times higher), then the cutter has to have a very long active surface, e.g. a long thermal knife penetrating more or less vertically.

Flame jets are one alternative to electrothermal devices. They utilize the energy of the basic fuel more efficiently, but they probably have higher thermal losses and they almost certainly would have to melt wider slots.

In short, thermal cutters do not look attractive for large-scale icebreaking.

Cutting ice with lasers

Lasers can transmit radiant energy over long distances through air, and they can develop very high power density in the target area. However, once the laser beam impinges on ice it is likely to act simply as a melting device, subject to the usual rate limitations. From very limited test data for a CO_2 laser, a process specific energy of 6×10^4 lbf/in.^{2} (414 MN/m^2) can be calculated for the cutting of freshwater ice. This is equivalent to melting with a thermal efficiency of 76%. This specific energy is comparable to the specific energy of a continuous water jet. To cut a slit 5 mm wide and 2 m deep at a traverse speed of 1.54 m/s (3 knots), the required laser power would be 6.4 MW if the process specific energy was 414 MN/m^2. Thus lasers do not seem to be practical for heavy duty ice cutting at the present time.

Cutting with water jets

High velocity water jets are capable of cutting ice. There are three types of jets that might be considered: 1) continuous jets operated at constant nozzle pressure, 2) continuous jets with pressure modulation, 3) pulsed jets firing intermittently. All have very high specific energy (greater than 10^4 lbf/in.^{2} when cutting ice), so that they cannot possibly be considered for bulk breaking. However, they are non-contact tools and they permit enormous power densities to be achieved, and so have to be considered as a potential means of cutting very thin slots.

For pulsed jets, fantastic pressures (comparable to high explosive detonation pressures) can be developed for single shots by laboratory apparatus. However, pulsed jets simply spall the surface of the target material, and there is no

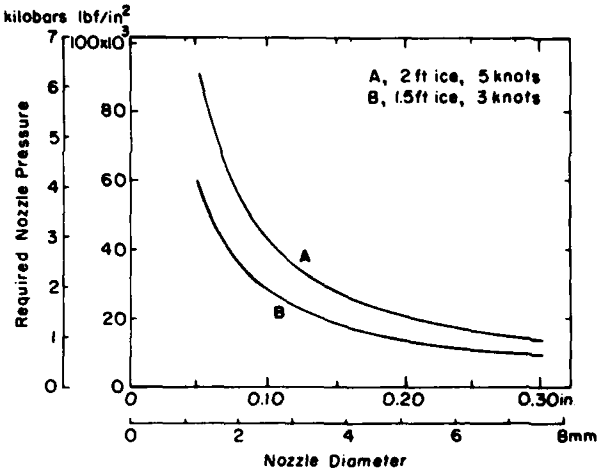


Figure 16. River icebreaker. Required nozzle pressure as a function of nozzle diameter to meet two different performance specifications.

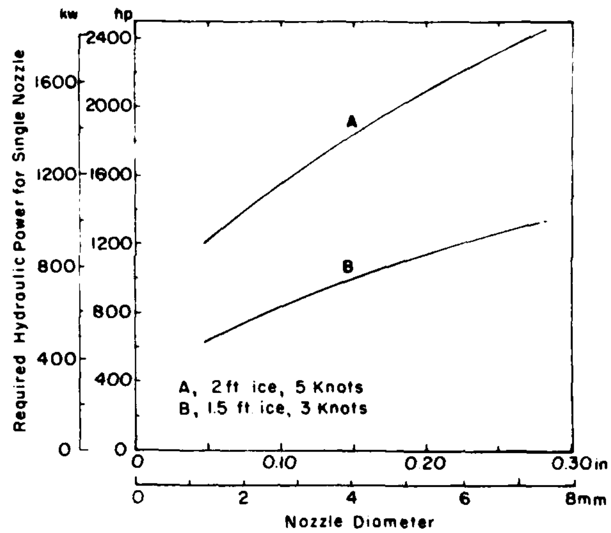


Figure 17. River icebreaker. Required hydraulic power for a single nozzle as a function of nozzle diameter.

reason to believe that they would be useful for cutting, even if workable equipment could be developed.

Modulated continuous jets have been proposed but not systematically tested, and it is difficult to see what advantages they would have. The apparatus for generating modulated high pressure jets would be prone to fatigue problems.

This leaves continuous jets as the sole contender for early application. Systematic experiments on the use of continuous jets for cutting ice have been made at nozzle pressures up to 100,000 lbf/in.^{2} (690 MN/m^2), and results have been summarized and assessed (Mellor, 1974). Preliminary design calculations have been made for simple jet devices intended as: 1) aids for icebreakers on lakes and rivers, 2) aids for polar icebreakers, 3) cutters for slicing a channel through sea ice, 4) protective cutters for piers, pilings and marine structures. Results are summarized in Figures 16-22.

One possibility for improving the ice-cutting performance of water jets would be to heat the feedwater, but the improvement might be only marginal at the high traverse speeds of icebreaking vessels.

For very deep penetration, continuous jets have been mounted on rotating heads that are capable of milling out a wide groove into which the nozzle itself can penetrate (a conventional nozzle is much wider than the slit cut by its jet)

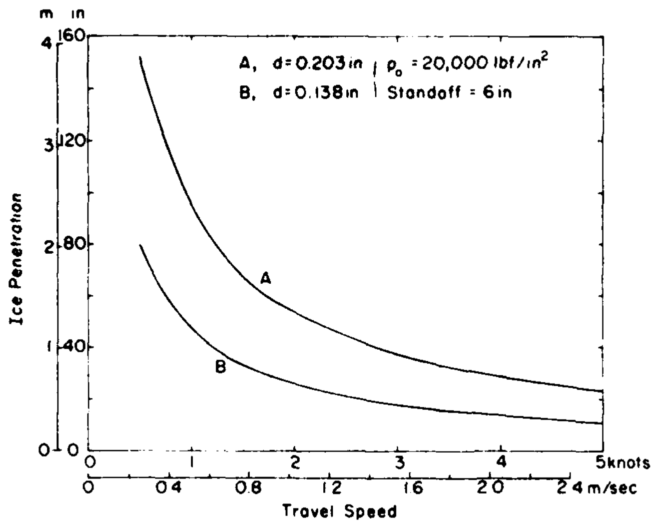


Figure 18. Lake icebreaker. Penetration as a function of travel speed for two different jet systems.

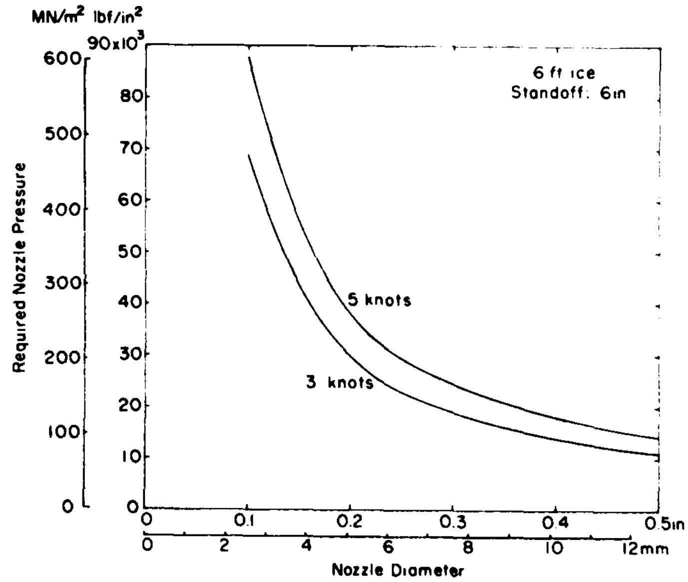


Figure 19. Polar icebreaker. Required nozzle pressure as a function of nozzle diameter for cutting of 6 ft of ice at 3 and 5 knots.

These devices do not appear to be of much interest in the present context, for a variety of reasons (low efficiency, unnecessary complexity, vulnerability to damage, simpler alternatives).

If very high pressures are contemplated, say over 30,000 lbf/in.² (207 MN/m²), the practical differences between small scale laboratory apparatus and high capacity field equipment should be kept in mind.

To sum up, water jets appear to have some potential for aiding icebreaking ships if very high power levels can be accepted. Additional development work would be needed to produce a large-scale prototype, and any proposals for large-scale applications ought to be given close professional scrutiny.

Novel concepts

Some concepts that are potentially applicable to icebreaking have not been tested in the field, in most cases because there are serious drawbacks.

Ice can be cut by tools that indent a surface in the normal direction, as distinct from cutting tools that shear or scrape parallel to the surface. Normal-indentation tools may be driven by a quasi-static thrust, as is the case with disc cutters and studded roller cutters, or they may be

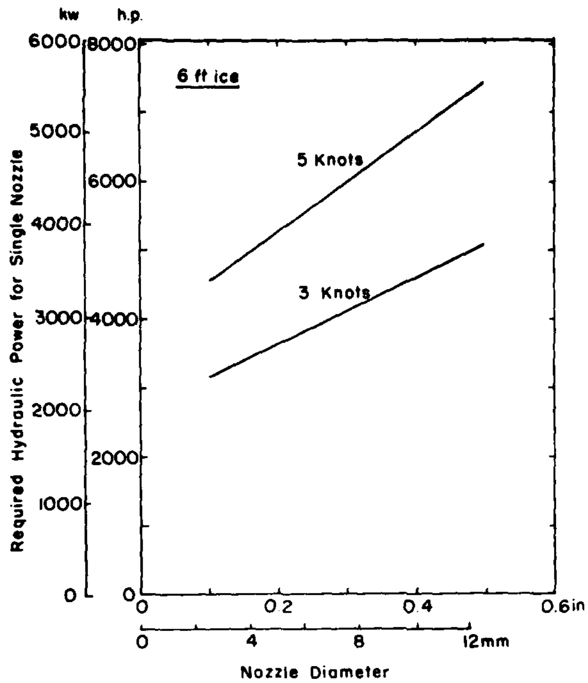
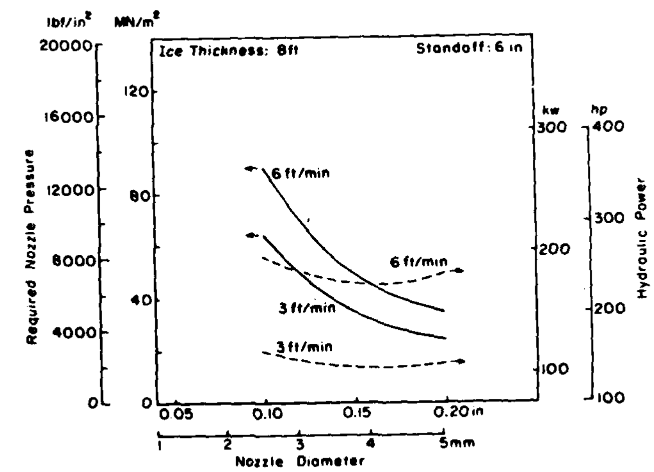


Figure 20. Polar icebreaker. Required hydraulic power for a single nozzle as a function of nozzle diameter.

Figure 21. Pipelaying cutter. Required nozzle pressure and hydraulic power as functions of nozzle diameter for penetration of 8 ft of ice at 3 and 6 ft/min.



driven by an inertial "hammering" mechanism, as is the case with pile drivers, impact breakers, percussive drills, and vibratory devices. The indentation action can also be produced by free projectiles, such as free-falling inert bombs or pellets, and projectiles fired from guns. Most of these concepts have been studied to the extent that their probable icebreaking capabilities can be evaluated in quantitative terms.

There have been various proposals for use of electrical energy in icebreaking. Internal absorption of high frequency electromagnetic radiation was considered by Hoekstra (1976) following Russian reports of relevant tests, but it was not judged to be a promising technique. Various types of pulsed discharges from capacitor banks have been proposed, including discharge between electrodes embedded in the ice, and exploding wire discharges. None of these are likely to provide the basis for a useful system. Direct impingement of an electron beam has been tried on frozen soil with discouraging results, and there is no reason to believe that the effect on ice would be much more favorable.

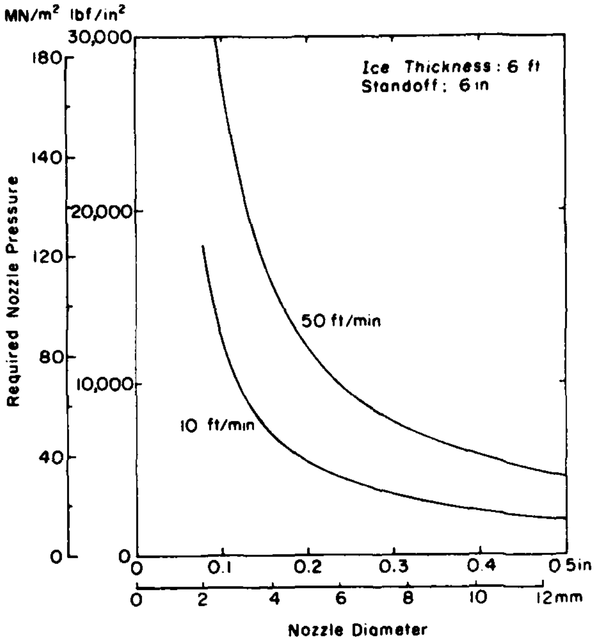


Figure 22. Pier protector. Required nozzle pressure as a function of nozzle diameter for penetration of 6 ft of ice with encroachment speeds of 10 and 50 ft/min.

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